**Canadian Conference - Pacific Conference on Earthquake Engineering 2023**

**Vancouver, British Columbia**

**June 25th – June 30th, 2023**

# Modification of 6th Generation National Seismic Hazard Model for Low Probability Earthquake Ground Motion Estimates in the Western Canadian Craton

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## ABSTRACT

The 2019 Canadian Dam Association guidelines and the 2020 Global Industry Standard on Tailings Management now require robust estimates of low probability earthquake ground motions, including for large mine tailings facilities in tectonically stable regions of western Canada. With recent scientific advances in ground motion models (GMM), site amplification estimation, and revised source zonation in the 6th Generation Canadian National Seismic Hazard Model (CanadaSHM6), there are now opportunities to test, and if necessary, revise, past seismic hazard estimates for this part of Canada.

We describe a seismic source model that uses area-weighted earthquake activity estimates from the western and eastern components of CanadaSHM6 and past published source zone models for the stable cratonic region of western Canada. We present seismic hazard results from a case study at an example site within our study area in northern Alberta. The next generation attenuation ground motion models (NGA-East) and two 2020 site amplification models developed for eastern and central North America provide estimates for 1/10,000 annual exceedance probability (AEP) spectral accelerations from peak ground acceleration (PGA) to 10 seconds. Uncertainties in earthquake activity rates and ground motion models, and site amplification are captured in logic trees. Spectral accelerations were calculated in the OpenQuake v3.11 software engine using the same standard deviation model as implemented for CanadaSHM6.

Mean accelerations at a 1/10,000 AEP are 7% to 12% lower than reported by Atkinson and Martens [1] at spectral periods from ~0.2 s to 2 s, and 2% lower to 30% higher at spectral periods from PGA to 0.2 s. The largest difference of 30% at 0.1 s spectral period is likely caused by the differences between the Atkinson and Boore [2] GMM compared to the 17 NGA-East GMMs. At a 1/2,475 AEP, mean accelerations are 7% to 68% lower than those available for the 2020 NBCC (based on CanadaSHM6) at all spectral periods, with the greatest differences at periods longer than ~1 s. Sensitivity analysis suggests that the differences between this assessment and CanadaSHM6 are largely from the use of the period-weighted NGA-East GMMs in this assessment. Fractile analysis confirms that uncertainties remain high despite the considerable technical advances incorporated in CanadaSHM6.

Keywords: Earthquake Hazard and Design Ground Motions, Canadian National Seismic Hazard Model

## INTRODUCTION

### Background

Probabilistic seismic hazard analysis (PSHA) for sites in tectonic regions with low to very low rates of historical earthquakes is an integral step in the design of critical infrastructure with a long design life such as dams, including embankments impounding mine tailings. While historical earthquakes and estimates of seismic hazard in these historically low earthquake activity regions are insignificant over relatively short time periods, critical infrastructure must be designed to withstand earthquake ground motions with low probabilities (e.g., 1/10,000 annual exceedance probability, AEP). The 2019 updated guidelines from the Canadian Dam Association and 2020 Global Industry Standard on Tailings Management indicate that low AEP ground motions should be considered in the design of critical mine tailings facilities in stable cratonic regions of Canada.

**Study Overview**

The scope of a site-specific PSHA is to develop a seismic source model to represent earthquake sources that contribute to the seismic hazard at the site. The seismic source model is used with selected source-to-site attenuation ground motion models (GMMs) to estimate ground motions at a range of spectral periods and annual exceedance probabilities (AEPs). The AEP of particular interest for engineering analyses undertaken subsequent to this study was 1/10,000.

One common approach for site-specific PSHA in low hazard regions of Canada is to use existing seismic source models, including the 6th-Generation Canadian Seismic Hazard Source Model (CanadaSHM6) [3]. CanadaSHM6 is the latest version of the source model used for Canada's national seismic hazard assessment, published in 2020 and used as the basis for the 2020 National Building Code of Canada (NBCC). Using the CanadaSHM6 model, however, does not necessarily meet the requirements of a site-specific study because it applies a national source model that may not account for the unique tectonic conditions that can drive the hazard at a particular site. In this paper, we present one example of how adaptations to the CanadaSHM6 can make it suitable for a site-specific seismic source model for sites located in the tectonically stable regions of western Canada. The PSHA approach and results described here can provide inputs suitable for geotechnical engineering analyses, including selection of earthquake acceleration time histories and stability analysis under static and seismic loads.

**REGIONAL GEOLOGICAL AND TECTONIC SETTING**

The study area considered for the PSHA (Figure 1) is within the Interior Plains of Canada that comprises geologically old (more than 1 billion years ago [Ga]) crystalline basement rock of the North American Craton. In places, these ancient rocks are overlain by a variable thickness of sedimentary sequences of the Western Canada Sedimentary Basin (WCSB). These sediments were deposited from the late Precambrian to Cenozoic (~1,470 Ma to 57 Ma) in a large, shallow sea resulting in an environment rich in hydrocarbons such as coal beds, and the sources and present-day reservoirs of oil and natural gas.

The study area chosen for the PSHA is underlain by the Cretaceous-age McMurray Formation of the WCSB. The McMurray Formation is a fluvial and estuarine deposit locally, comprising fine- to coarse-grained quartz-rich sand and sandstone interbedded with lesser amounts of silt, mud, clay, and, less commonly, coal beds. The McMurray Formation contains economically important deposits of bitumen that are now extensively mined in the region. The depth to the North American Craton Precambrian basement rocks is 200 m to 400 m in the study area.

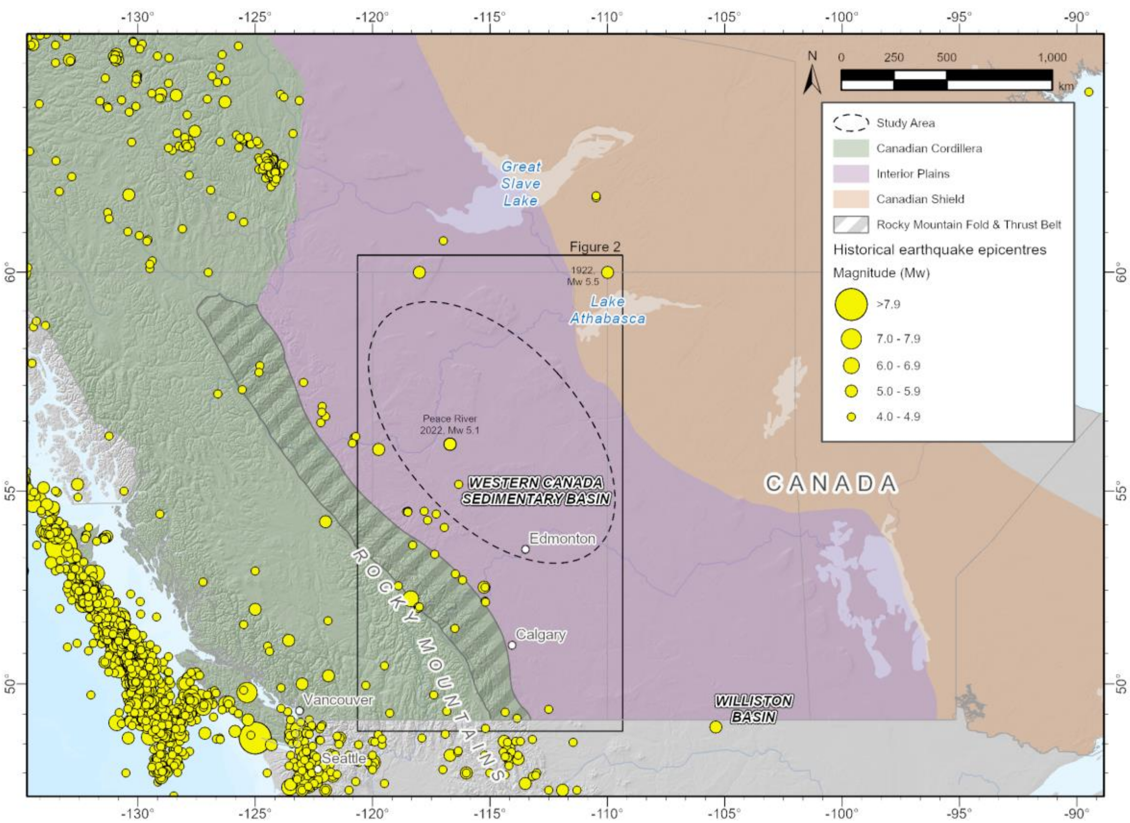


*Figure 1. Historical earthquake epicenters ($M_w \geq 4$) in southwestern Canada. Geological regions are from Natural Resources Canada (NRCan), via [https://open.canada.ca/data/en/dataset/a3dfbaf4-1b20-4061-aa0a-e7a79953f52d](https://open.canada.ca/data/en/dataset/a3dfbaf4-1b20-4061-aa0a-e7a79953f52d).*

The study area is within a relatively seismically quiescent region of central Canada, located more than 1,000 km from the closest present-day active tectonic plate boundary in western North America. Regional tectonic stress is compressional with a north-northeast to south-southwest (NNE-SSW) orientation [4]. The regional strain rate decreases northeastward from the Canadian Cordillera to the WCSB. Consequently, historical rates of earthquake occurrence are relatively higher west of the study area in the Foothills at the eastern edge of the Rocky Mountain Fold and Thrust Belt (Figure 1). The largest recorded earthquake within about 500 km is a moment magnitude ($M_w$) 5.5 in 1922 and with an epicenter in northern Alberta (Figure 1).

Since 2011, Alberta has experienced an increase in recorded earthquakes. Most of these earthquakes can be attributed to the extensive use of hydraulic fracturing, and waste-water injection wells (e.g., [5]). Most earthquake hypocenters are within the Foothills region (FTH, Figure 2) where earthquakes with local magnitudes ($M_L$) up to $M_L$ 4.8 have been recorded [5]. There was also a shallow (5 km) $M_w$ 5.1 earthquake in the Peace River area on 30 November 2022, which was preceded and followed by numerous $M_w$ 4+ foreshocks/aftershocks. The Peace River area has two proposed active clusters of seismicity [5] – potentially induced seismicity related to wastewater disposal 40 km east of Peace River, and natural seismicity associated with the Peace River Arch (Figure 2). These earthquakes demonstrate that induced seismicity occurs within and near to the study area. However, seismic hazard from induced seismicity is explicitly excluded in this analysis because there are large short-term changes in the rates of induced seismicity based on market fluctuations. Seismic hazard from natural earthquakes associated with the Peace River Arch is modelled with uniform-area seismic sources in a site-specific source model.

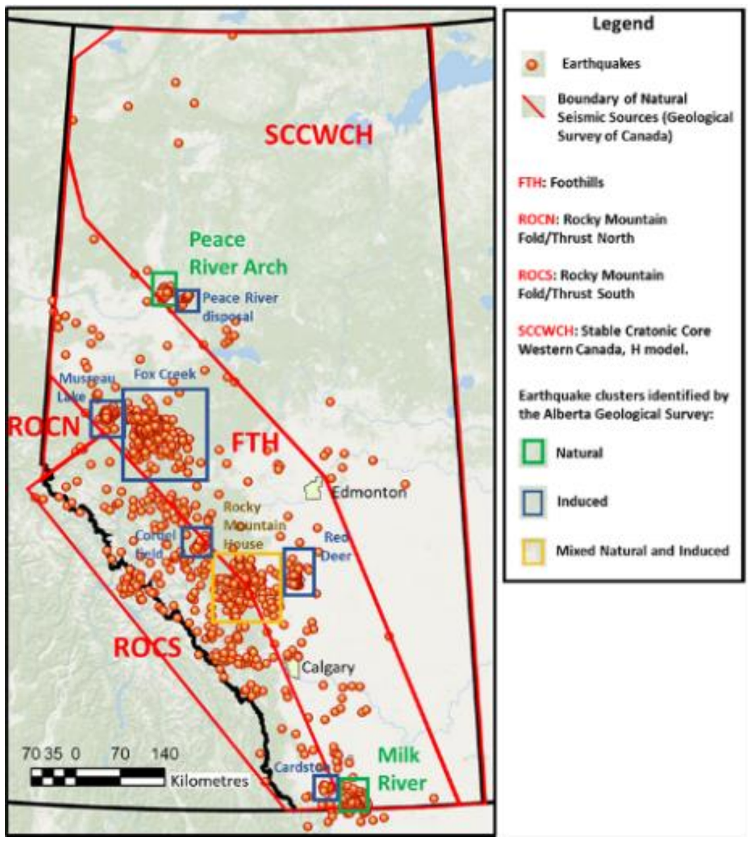


*Figure 2. Earthquake epicenters and CanadaSHM6 source zones in Alberta, showing natural and induced seismicity near the study area. Figure from the Alberta Energy Regulator, via: https://ags.aer.ca/research-initiatives/natural-earthquakes.*

## PSHA APPROACH

Probabilistic seismic hazard analysis (PSHA) estimates the likelihood that specified earthquake ground motions will be exceeded within a specified time. In this study, we apply the classical PSHA methods of Cornell [6]. This approach considers all possible seismic sources expected to affect a site, their rates (or, alternatively, probabilities) of occurrences, and uses ground motion models to estimate the expected ground motions that will occur for earthquakes produced by these sources. This method relies on the assumption that earthquakes occur randomly in space and time (i.e., a Poisson process). The seismic source model and ground motion models implemented in the PSHA are described in the subsequent sections.

The probabilistic analysis for this study was undertaken using the OpenQuake Engine software (v3.11.4) developed by the Global Earthquake Model (GEM) Foundation [7].

## SITE-SPECIFIC SEISMIC SOURCE MODEL

### Overview

A seismic source model defines known active and potentially active seismic sources that can contribute to the earthquake ground motions at the site or sites under consideration. These sources can be large and small areas of historical earthquake epicenters, tectonic terrains, or geophysically defined regions. Earthquake sources associated with the rupture areas of large historical earthquakes are considered where applicable, as are faults where there is evidence of surface displacement during the Upper Pleistocene stage of the Pleistocene Epoch (i.e., the last about 130,000 years). The seismic source model is defined in terms of parameters including source location, source geometry, faulting mechanisms, maximum earthquake magnitude, and earthquake recurrence models.

In this section of the paper, we present a seismic source model specific to our study area within the western Canada cratonic core in Alberta. The seismic source model, shown in Figure 3, incorporates uniform-area sources intended to represent shallow crustal earthquakes within about 500 km of sites within the study area. Uniform-area sources are derived from two existing source models, as discussed in the following sections. No shallow crustal fault sources are included in the source model because no faults with proven recent activity have been mapped within the study area.

### Central Canadian Craton Model

Atkinson and Martens [1] completed a seismic hazard study of the Fort McMurray region. As part of their study, Atkinson and Martens developed a uniform-area source model to characterize the stable cratonic core of Canada. This model, named the central Canadian (CC) craton model, was intended to represent a stable cratonic region within which the seismicity rates are broadly analogous to those expected in the Fort McMurray region. The CC craton model was developed by revising the North American (NA) craton model defined in 2006 by Fenton et al. [8]. The NA craton model extent was based on the North American continent with its actively deforming regions excluded. Actively deforming regions were defined by Fenton et al. [8] as all regions of non-Precambrian crust, all passive margins and areas within 200 km inland of passive margin coasts, and areas within 200 km of regions of Phanerozoic (last 500 Ma) deformation.

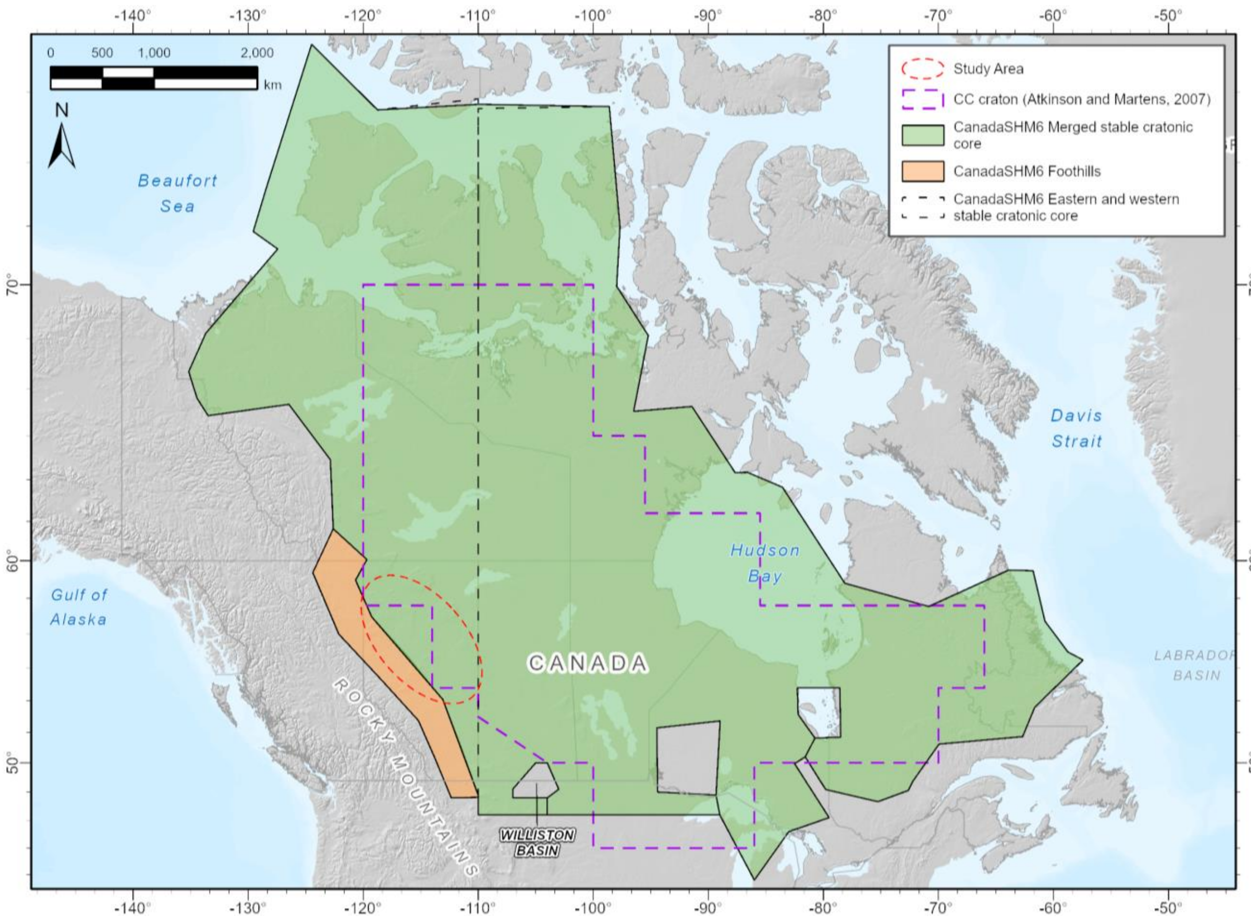


*Figure 3. Uniform-area sources of the seismic source model implemented for the study area in this PSHA.*

Atkinson and Martens [1] defined the boundaries of their CC craton model by excluding some areas of Phanerozoic rifting that had been included within the NA craton model. The exclusion of the Phanerozoic rift zones resulted in earthquake occurrence rates in the CC model being lower than those in the larger NA model by about a factor of three. Atkinson and Martens [1] proposed that the CC craton model was more representative of the central Canadian stable craton than the broader NA craton model. While they tested various combinations of the CC and NA craton models with different weightings, the preferred seismic source model weighted the CC craton model at 90% and the NA craton model at 10%.

Following review of the CC craton and NA craton models and the supporting documentation provided by Atkinson and Martens [1], we incorporated the CC craton model into the seismic source model specific to our study area. The NA craton model was not implemented in our study because we followed the findings of Atkinson and Martens [1]. For implementation of the CC craton model in the OpenQuake software engine, area-normalized earthquake magnitude-recurrence parameters from Atkinson and Martens [1] were converted to non-normalized rates.

**Sixth-Generation Canadian Seismic Hazard Model**

Along with the Atkinson and Martens [1] model, we also reviewed the latest national seismic hazard consensus model for Canada, the sixth-generation Canadian seismic hazard model (CanadaSHM6). This model was developed by the Geological Survey of Canada [3] and was used to determine hazard values for the 2020 edition of the National Building Code of Canada (2020 NBCC). We downloaded digital files from the preliminary release of CanadaSHM6 from the GSC Open File Report 8629 (published 23 January 2020) [3] and GSC Open File Report 8630 (published 19 October 2020, last updated 29 November 2021) [9].

The CanadaSHM6 has three location-based seismic source models: western Canada, eastern Arctic Canada, and southeastern Canada. The study area in Alberta is located within the cratonic core of Canada, an area of historically low seismicity on stable, continental crust. In CanadaSHM6, stable shallow crustal seismicity is generally captured within the southeastern Canada source model. However, the study area is located west of the nearest area source in the southeastern Canada source model, which is bounded on its western side at 110°W (the Alberta-Saskatchewan border). The study area is, therefore, located within the western Canada source model of CanadaSHM6.

The western Canada source model is comprised of a single model. By contrast, the southeastern Canada source model comprises three alternative sub-models: the Historical (H2, weighted 0.4), Regional (R2, weighted 0.2), and Hybrid (HY, weighted 0.4) sub-models. Source parameters in the H2 sub-model are based on historical earthquake locations and magnitudes. The R2 sub-model was developed using the regional geological criteria as the basis for selection of the seismic source parameters, and the HY sub-model was developed using both historical earthquake data and regional geological parameters.

Three uniform-area sources in the western Canada source model are near the study area (Figure 3). These three sources are as follows:

- Stable Cratonic Core, Western Canada (SCCWC) – represents the western portion of the stable cratonic core.
- Stable Cratonic Core, Eastern Canada (SCCECHW) – represents the eastern portion of the stable cratonic core, with earthquake activity rates based on historical seismicity and the intra-cratonic Williston Basin excluded as a separate source.
- Foothills (FTH) – represents the eastern foothills of the Rocky Mountains.

**Modifications to CanadaSHM6 Craton Model**

The Western Canada regional model of CanadaSHM6 includes separate uniform-area sources to represent western and eastern portions of the stable cratonic core, as listed above. The study area is located within the western stable cratonic core area source in the Western Canada regional model of CanadaSHM6, with the closest boundary of the eastern stable cratonic core area source being approximately 100 km east of the study area. These two stable cratonic core area sources are split at the 110°W meridian, an arbitrary boundary that does not reflect a change in seismotectonic properties.

Earthquake occurrence rates for the eastern stable cratonic core area source in CanadaSHM6 are significantly higher than those for the western stable cratonic core, as shown in the magnitude-frequency distribution in Figure 4. Larger magnitude earthquakes incorporated into the eastern stable cratonic core occurred more than 500 km east of the study area. Only a few small ($M_w$<2.5) earthquakes in the eastern stable cratonic core are known to have occurred within 500 km of the study area. On this basis we assessed that the use of an unaltered CanadaSHM6 eastern stable cratonic core, based on earthquakes at great distances from sites in the western stable cratonic core east of the Rockies, was inappropriate for this study.

To smooth the earthquake occurrence rates for the eastern and western stable cratonic core uniform-area sources, the following approach was applied. A merged stable cratonic core area source geometry was created by combining the eastern and western stable cratonic cores. Annual earthquake occurrence rates for the merged area source were calculated from an area-weighted sum of occurrence rates from the eastern and western stable cratonic core area sources.

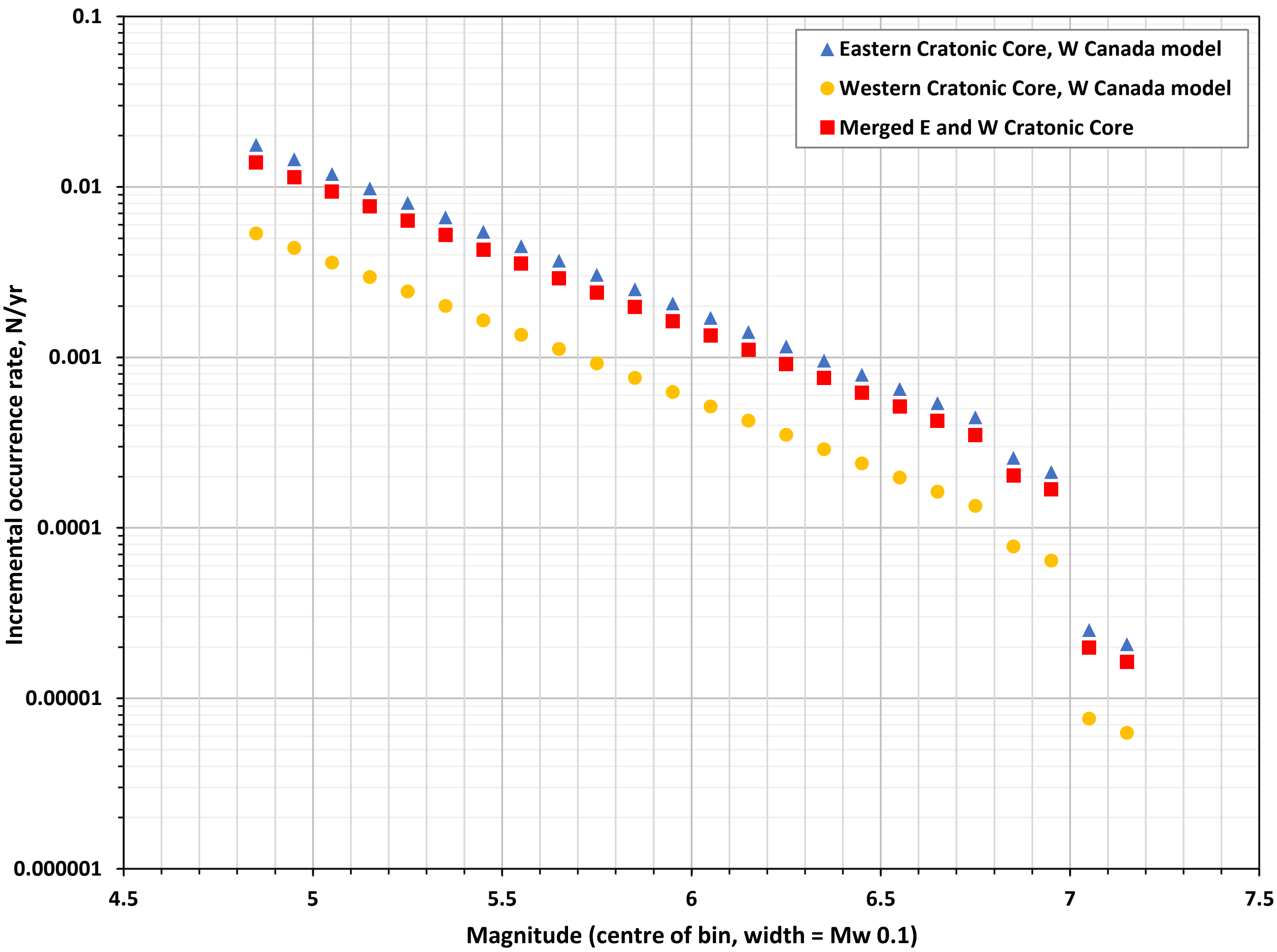


*Figure 4: Earthquake occurrence rates for the eastern and western stable cratonic core sources in the CanadaSHM6 western regional model (W Canada), along with occurrence rates for the merged stable cratonic core.*

**Earthquake Catalogue**

Earthquake occurrence parameters for the CC craton and CanadaSHM6 uniform-area sources incorporated in the site-specific seismic source model were implemented based on the parameters published by Atkinson and Martens [1] and Kolaj et al. [9], with modification of the CanadaSHM6 annual occurrence rates as described above. Earthquake occurrence parameters for both models, however, were based on earthquake catalogues that do not extend to the present day.

Atkinson and Martens [1] parameterized the CC craton from an earthquake catalogue through 2005. North of 40°N, records were taken from the GSC database and for areas south of 40°N, records were taken from USA sources (Incorporated Research Institution for Seismology [IRIS] and US Geological Survey National Earthquake Information Center [NEIC]).

The Seismic Hazard Earthquake Epicenter File (SHEEF2010) catalogue developed by Halchuk et al. [10] supports the earthquake occurrence rates used in CanadaSHM6. The SHEEF2010 catalogue includes earthquakes with an original catalog magnitude (typically $M_L$ or $m_N$) of 2.5 or higher. Magnitudes were converted to moment magnitude ($M_w$), using region-specific relationships described in [10].

Many earthquakes have occurred in the study area following the compilation of the SHEEF2010 catalogue. It was therefore important to check whether more recent seismicity warranted adjustment of earthquake occurrence rates implemented in the uniform-area source models considered. We looked at earthquakes $M_w \geq 2.5$ from the GSC National Earthquake Database (NEDB) online earthquake catalogue from 2011 to the present located within about 1,000 km of the study area. This catalogue is referred to as the "post-SHEEF2010 catalog". These records comprise various measures of earthquake magnitude which were converted to $M_w$ following the conversion relations of Halchuk et al. [10]. A comparison of the SHEEF2010 earthquake catalog with a summed post-SHEEF2010 and SHEEF2010 catalogue showed that more recent earthquakes (i.e., post-SHEEF2010) have not significantly impacted earthquake occurrence rates since the publication of the SHEEF2010 catalogue.

Rates of seismicity were comparable in both the SHEEF2010 and post-SHEEF2010 catalogue. As a result, recalculation of seismicity rates based on an updated catalog was not required and we applied the rates from Atkinson and Martens [1] and Kolaj et al. [9].

### Final Model Selection and Weighting

The seismic hazard assessment in this study uses the following stable shallow crustal area sources (Figure 3) and weights:

- The Central Canadian (CC) craton area source, developed by Atkinson and Martens [1]. Weighted 80%.
- CanadaSHM6 source models, presented by Kolaj et al. [9]. Weighted 20% and comprising the following sources:
  - Stable cratonic core area source, representing a merge of the eastern and western stable cratonic core area sources in CanadaSHM6.
  - Foothills area source.

A greater weight was selected for the CC craton model of Atkinson and Martens [1] to represent the central Canadian craton because it is a robust, site-specific study that included a detailed analysis and characterization of the seismicity of the Canadian Craton in central Canada. They developed earthquake activity rates for this tectonically stable, central craton without the larger historical and paleoseismic earthquakes in cratonic regions of the USA and eastern Canada. Atkinson and Martens [1] argued that the stable Canadian craton includes the area in the Prairie provinces from western Ontario to western Alberta.

The CanadaSHM6 model was included as an alternative to the CC craton model, but with a lower weight to reflect a stable cratonic core that is more broadly defined in the national-scale seismic hazard model. The CanadaSHM6 model was developed for all of Canada, primarily to provide estimates of 1/2,475 AEP ground motions to support the 2020 NBCC rather than a more site- or region- specific analysis for an AEP of 1/10,000 for sites in Alberta east of the Rocky Mountains in the western Canada stable cratonic core.

Sensitivity analyses of the model weights, with the CC craton model weight varied between 80% and 40% in increments of 10%, indicated that greater weighting of the CC craton model resulted in relatively lower mean spectral accelerations and greater weighting of the CanadaSHM6-derived model results in relatively larger mean spectral accelerations.

## GROUND MOTION MODELS

The ground motion model (GMM) is a key component of seismic hazard analysis. GMMs provide estimates of earthquake ground motions at a site (e.g., PGA and spectral acceleration response ordinates) as functions of the earthquake magnitude, source-to-site distance, local site ground conditions, and other factors. For this site-specific seismic hazard assessment, we use the final suite of 17 GMMs developed for the Next Generation Attenuation for Central and Eastern North America (CENA) project (NGA-East, PEER Report 2018-08 [11]). NGA-East median ground motions are suitable to model earthquake ground motion attenuation for this study because they were developed with a robust process for a tectonic region (i.e., stable continental regions) similar to that in the study area.

As described by Atkinson and Martens [1], the GMM used in the Fort McMurray seismic hazard study was that developed by Atkinson and Boore [2], which was derived for “hard rock” sites equivalent to the National Earthquake Hazards Reduction Program (NEHRP) site class A ($V_{S30}$ >1,500 m/s). Atkinson and Martens [1] use this GMM to calculate hazard results for soil Site Class A conditions and adjust results for soil Site Class C conditions using scaling factors. The Atkinson and Boore [2] GMM could not be readily used in the present study without adjustment to account for local site amplification because it has a $V_{S30}$ of 360 m/s. Atkinson and Boore [2] is also considered to have been superseded by the final NGA-East GMMs.

As described by Kolaj et al. [12], CanadaSHM6 is implemented with two equally weighted suites of GMMs. Firstly, the preliminary 13 NGA-East GMMs (PEER Report 2017-03 [13,14]) with the Atkinson and Adams (AA13) [15] standard deviation model developed for CanadaSHM5. Secondly, the AA13 median GMMs and standard deviation model as used in the previous, 5$^{th}$, generation of the Canadian national seismic hazard model. As noted in the addendum to PEER Report 2017-03 [13,14], the preliminary 13 NGA-East GMMs have been superseded. The final suite of NGA-East GMMs is, therefore, considered more appropriate for implementation in this study than the older GMMs applied with CanadaSHM6.

### Standard Deviation Model

As a limited CENA dataset was used to develop the NGA-East GMMs, standard deviation models from other regions, including the western United States and Japan, were used to inform the extrapolation of CENA standard deviations to large magnitudes and frequencies outside of the 1 Hz to 10 Hz frequency range. The standard deviation models published in NGA-East have high sigma values and lead to a large discrepancy between median and mean ground motions. As such, the NGA-East standard deviation models were not implemented with the median ground motions for CanadaSHM6 for this study. The 17 NGA-East

GMMs are instead implemented with using AA13 standard deviation model that is also used for calculating ground motions from CanadaSHM6 for the 2020 NBCC.

**Site Amplification Models**

Since the development of CanadaSHM6, the NGA-East GMMs have been used to update the US National Seismic Hazard Maps for the CENA region [16]. Recommendations for the ergodic site amplification model in the CENA were provided by Stewart et al. [17] and Hashash et al. [18] to produce the earthquake ground motion intensity measures for site conditions with a $V_{S30}$ less than the 3,000 m/s reference hard-rock condition, as adopted for the NGA-East GMM development. The $V_{S30}$ is time-averaged shear-wave velocity of the 30 m below the ground surface or a selected reference surface. We applied the two 2020 site amplification models in [17] and [18] to adjust the site condition from the NGA-East reference hard-rock condition with a $V_{S30}$ of 3,000 m/s to a $V_{S30}$ condition of 360 m/s.

## SOURCE MODEL AND GMM UNCERTAINTY

This study uses a full source model and GMM logic trees to incorporate uncertainty in model input parameters. By contrast in CanadaSHM6, the two magnitude-frequency distribution (MFD) branches of the logic tree, comprising alternative recurrence parameter sub-branches and three alternative maximum magnitude sub-branches, were collapsed into a single MFD branch for computational efficiency. The use of the full logic tree for site-specific PSHA allows a greater range of uncertainties to be captured in the hazard results when compared the national-level results based on CanadaSHM6.

Figure 5 shows the logic tree implemented in this study. Parameters and weights for CanadaSHM6 sources are taken from Kolaj et al. [9] with values merged through an area-weighted combination where necessary for the merged stable cratonic core area source. Parameters and weights for the CC craton are taken from Atkinson and Martens [1]. Period- and model-dependent weights for the final suite of 17 NGA-East GMMs are implemented as recommended by Goulet et al. [11].

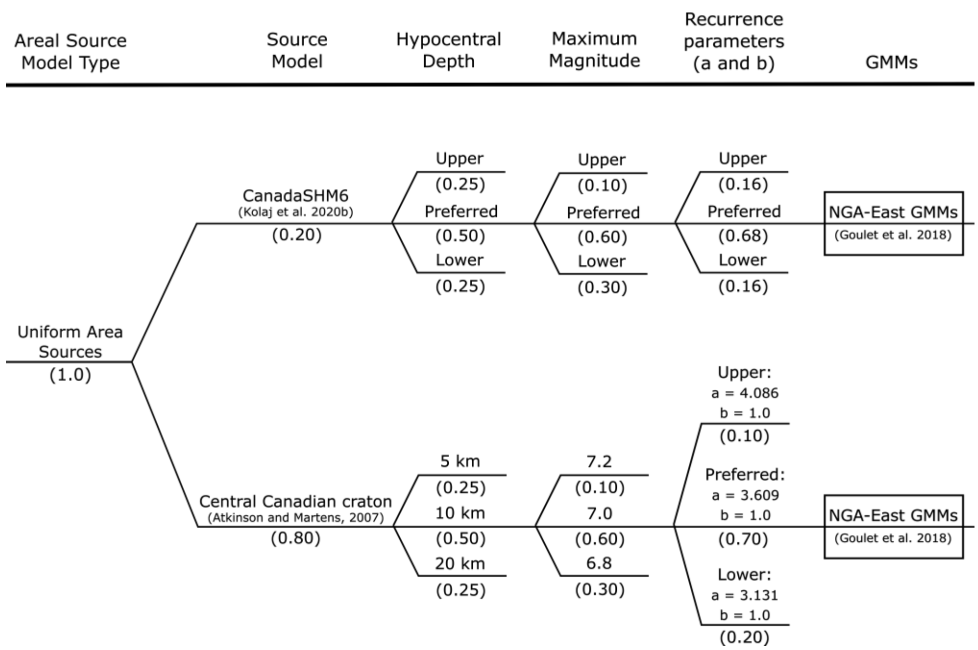


*Figure 5: Logic tree for the site-specific PSHA.*

## SAMPLE SEISMIC HAZARD RESULTS

This section presents sample seismic hazard results for a case study representative of sites in Alberta in the western Canada stable cratonic core. The case study PSHA is undertaken for a site ground condition represented by a $V_{S30}$ of 360 m/s (equivalent to the NEHRP site class C/D boundary). Ground motions are calculated for AEPs of 1/10,000 and 1/2,475, and spectral periods ranging from PGA to 10 s.

Figure 6 shows 5%-damped mean and fractile uniform hazard response spectra (UHRS) for AEPs of 1/10,000 and 1/2,475. The fractile UHRS indicate that there are large uncertainties in the hazard results, primarily driven by variation among the suite of 17 NGA-East GMMs. Figure 7 presents the results of magnitude-distance deaggregation of the mean UHRS shown in Figure 6 at PGA and 1.5 s spectral periods. A key feature of the magnitude-distance deaggregation is the general lack of scenarios characterized by the mean hazard. This is represented by larger epsilon (ε) values, shown by the yellow and red in Figure 7.

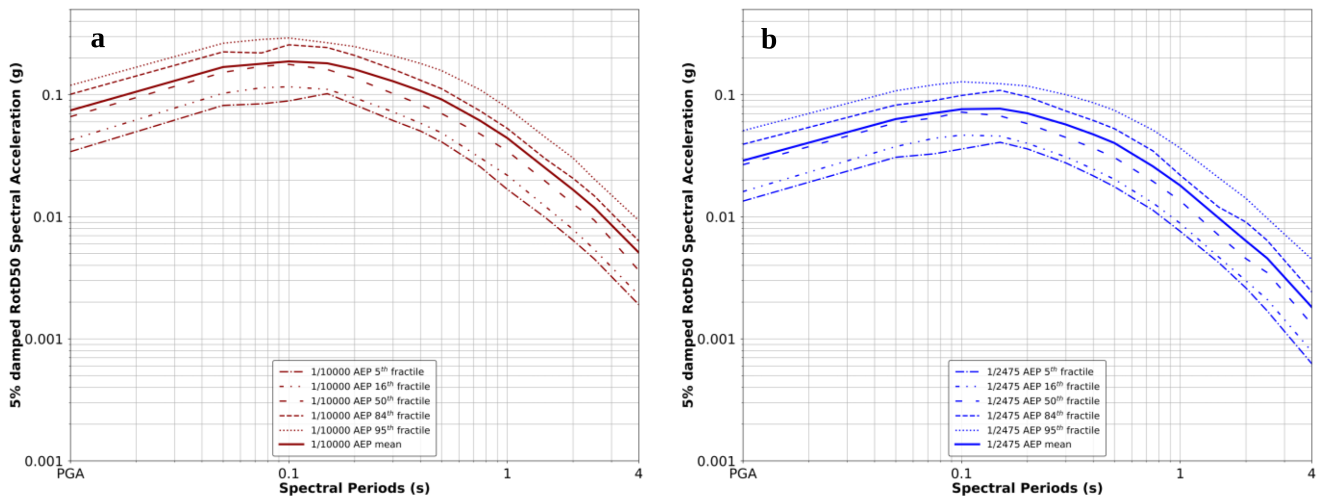


*Figure 6: 5%-damped mean and fractile UHRS for [a] 1/10,000 AEP and [b] 1/2,475 AEP.*

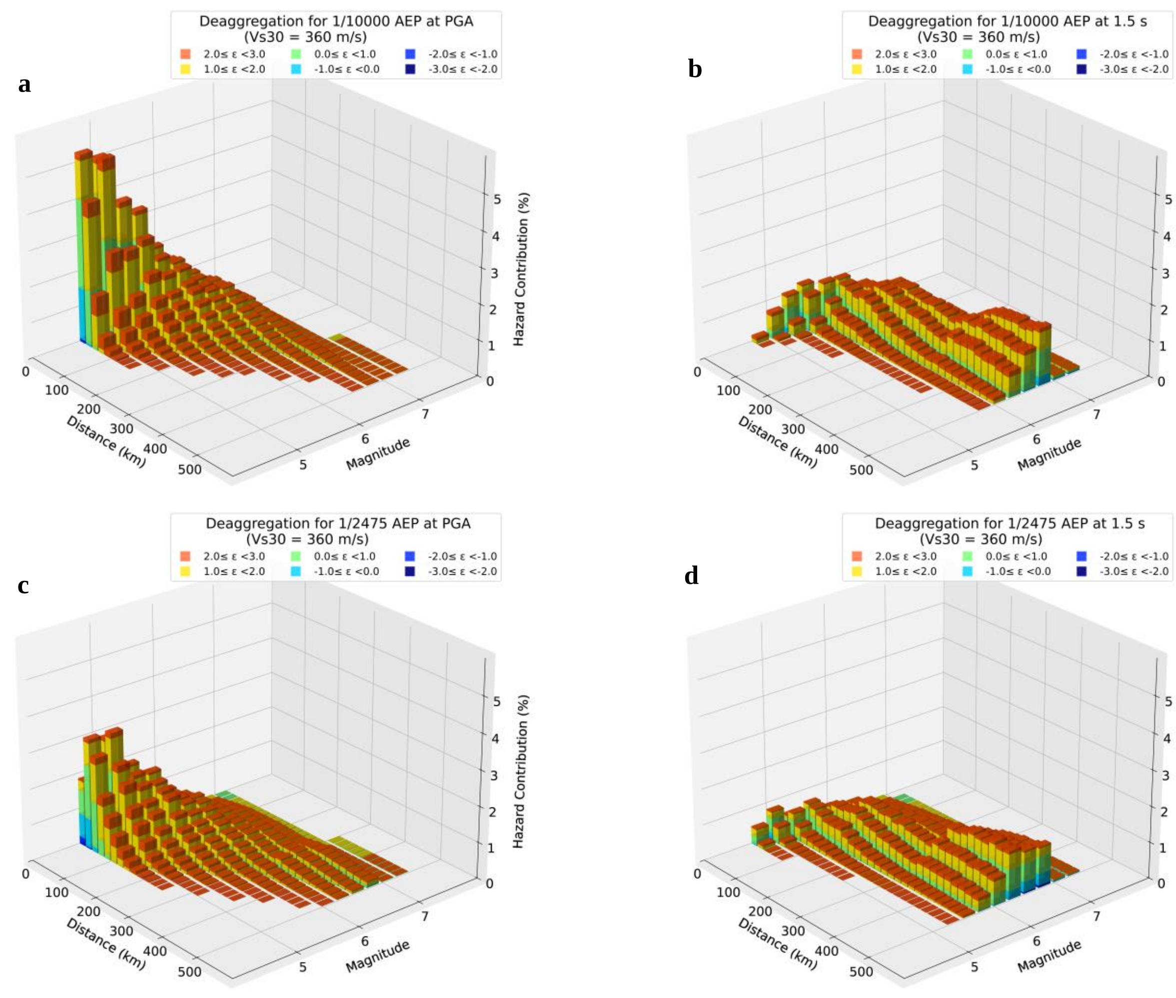


*Figure 7: Magnitude-distance-epsilon disaggregation for [a] 1/10,000 AEP at PGA, [b] 1/10,000 AEP at 1.5 s, [c] 1/2,475 AEP at PGA, and [d] 1/2,475 AEP at 1.5 s spectral period.*

## DISCUSSION

The seismic source model developed for sites within the study area in Alberta is based on the CC craton and CanadaSHM6 seismic source models presented by Atkinson and Martens [1] and Kolaj et al. [9] respectively. We implemented these existing source models with adjustment to the CanadaSHM6 stable cratonic core source zones (as described above) in order to make the source model specific to this area in the western Canadian cratonic core. We also implemented the final suite of 17 NGA-East ground motion models in place of the GMMs previously applied. As a result of these adjustments, the results presented for the case study differ from those presented in the previous studies.

Figure 8 presents a comparison of the following mean uniform hazard response spectra:

- $V_{S30}$ = 360 m/s results from the present study.
- Site class C results from Atkinson and Martens [1] for the Fort McMurray region, using the preferred 90% Central Canadian (CC) craton and 10% North American (NA) craton weightings.
- $V_{S30}$ = 360 m/s results based on CanadaSHM6, accessed from the Natural Resources Canada website (NRCan) [19].

Figure 8 shows that the results from this study are generally comparable to the results from Atkinson and Martens [1]. The largest difference, at 0.1 s spectral period, is attributable to the difference in the Atkinson and Boore [2] GMM compared to the 17 NGA-East GMMs we apply. Figure 8 also shows that the results of this study are significantly lower than the results calculated from CanadaSHM6. Table 1 presents the percentage difference between the results of this study and the two previous studies, for AEPs of 1/2,475 and 1/10,000. We note that 1/10,000 AEP spectra are not available for CanadaSHM6 on the seismic hazard calculator tool available from NRCan [19]. CanadaSHM6 is primarily intended for use to calculate seismic hazard values for the 2020 NBCC at a minimum AEP of 1/2,475, so our use of CanadaSHM6 sources for calculation at the 1/10,000 AEP can be considered a limitation of the study.

Hazard associated with induced seismicity was explicitly excluded from this analysis because there are large short-term changes in the rates of induced seismicity based on market fluctuations. However, we note that there are numerous recorded examples of mining-induced earthquakes in Alberta, including in the region considered in this study. An assessment of the impact of induced seismicity on hazard at sites in the study region would require further work.

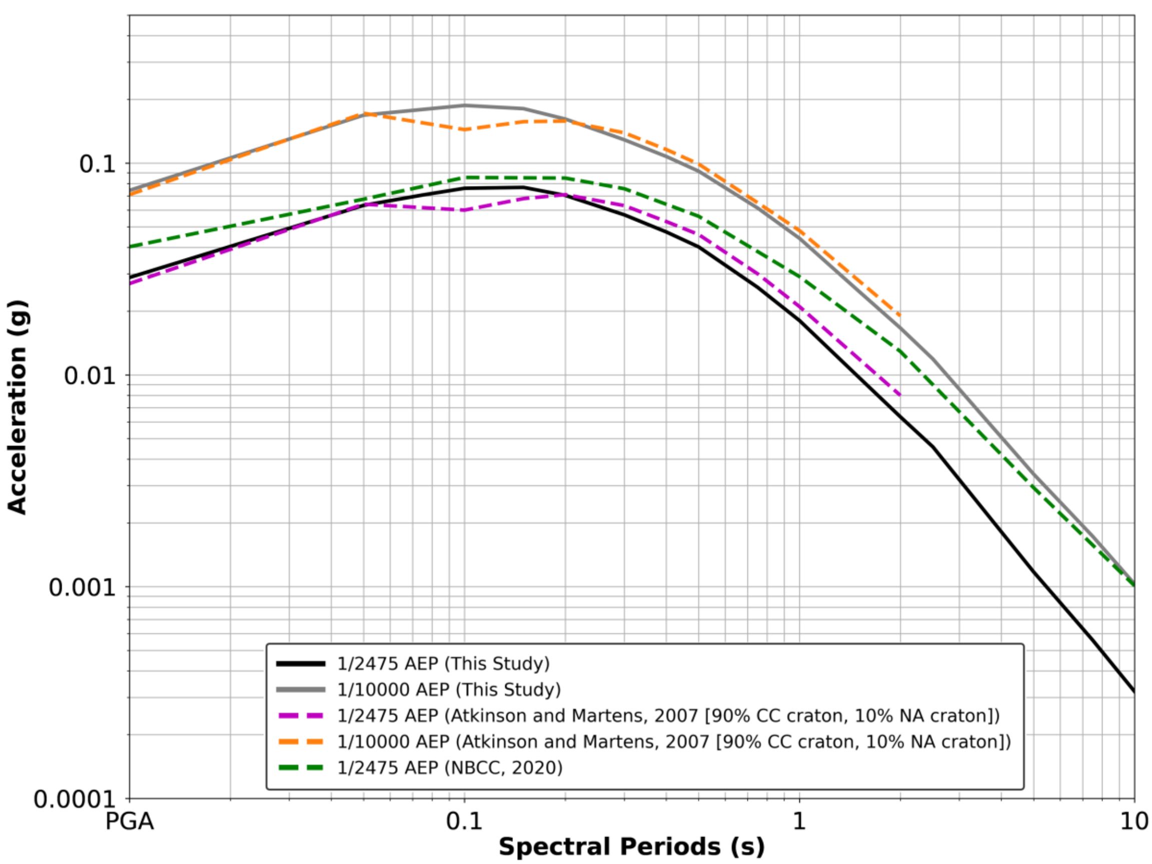


*Figure 8: Comparison of 5%-damped mean UHRS from this study, Atkinson and Martens [1], and 2020 NBCC.*

*Table 1: Percentage difference between mean accelerations from this study and the results from Atkinson and Martens (AM2007) and CanadaSHM6 (NBCC2020).*

| | **Difference in mean acceleration compared to this study (%)[1,2]** | | |
|---|---|---|---|
| **Spectral Period (s)** | **AM2007, 1/2,475 AEP** | **NBCC2020, 1/2,475 AEP** | **AM2007, 1/10,000 AEP** |
| PGA | -6.8 | 28.4 | -4.7 |
| 0.05 | 1.3 | 6.5 | 2.0 |
| 0.1 | -26.8 | 11.1 | -30.1 |
| 0.2 | 0.8 | 17.1 | -2.2 |
| 0.3 | 9.5 | 24.7 | 7.3 |
| 0.5 | 12.6 | 28.3 | 7.5 |
| 1.0 | 14.1 | 38.0 | 8.1 |
| 2.0 | 20.8 | 50.9 | 12.4 |
| 5.0 | n.p. | 60.0 | n.p. |
| 10.0 | n.p. | 68.3 | n.p. |

1. Positive percentage indicates a larger acceleration compared to the results of this study.
2. n.p. = acceleration not provided at this spectral period.

## CONCLUSIONS

In this paper we present an example of modification to the sixth-generation Canadian seismic hazard model (CanadaSHM6) for application in PSHA studies for sites in Alberta, within the western portion of the Canadian craton. To demonstrate the effect of these modifications, we present a case study for an example site in northern Alberta. Seismic hazard results for this case study are provided at AEPs of 1/10,000 and 1/2,475. The seismic source model implemented for the case study and relevant to sites within the study area is derived from existing source models from a previous Fort McMurray seismic hazard study (CC craton of Atkinson and Martens [1]) and the sixth-generation Canadian seismic hazard model (CanadaSHM6) [3]. The CanadaSHM6 uniform-area sources are modified to remove an arbitrary boundary at 110°W longitude and reduce the influence of larger earthquake occurrence rates in the eastern portion of the cratonic core associated with larger earthquakes well beyond the area of interest in this study. The final suite of 17 NGA-East ground motion models and two recent (2020) site amplification models developed for central and eastern North America are used to calculate ground motions in the case study.

Mean acceleration results from the case study presented are higher than those reported by Atkinson and Martens [1] for periods of PGA to 0.2 s at the 1/10,000 AEP, but lower at longer periods. The largest difference, at 0.1 s, is likely attributable to the difference in the GMMs used in the two studies. The case study results at 1/2,475 AEP are 7% to 68% lower than mean accelerations available for the 2020 NBCC (based on CanadaSHM6) at all spectral periods, with the greatest differences at periods longer than 1 s.

## ACKNOWLEDGMENTS

The authors acknowledge their use of the OpenQuake Engine software (v3.11.4), developed by the Global Earthquake Model (GEM) Foundation. We are grateful for inputs provided by our WSP colleagues in Canada, USA, and New Zealand.

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